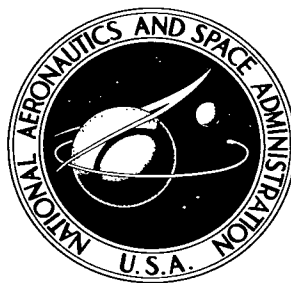


NASA TECHNICAL NOTE



NASA TN D-3720

NASA TN D-3720



STELLAR EVOLUTION I

CALIBRATION OF THE HERTZSPRUNG-RUSSELL DIAGRAM IN TERMS OF AGE AND MASS FOR MAIN-SEQUENCE B AND A STARS

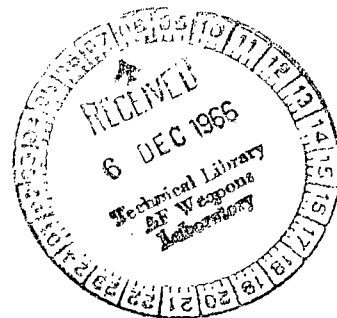
by T. Kelsall

Goddard Space Flight Center

and

Bengt Strömgren

Institute for Advanced Study, Princeton, N. J.





STELLAR EVOLUTION I
CALIBRATION OF THE HERTZSPRUNG-RUSSELL DIAGRAM
IN TERMS OF AGE AND MASS FOR MAIN-SEQUENCE B AND A STARS

By T. Kelsall

Goddard Space Flight Center
Greenbelt, Md.

and

Bengt Strömgren
Institute for Advanced Study, Princeton, New Jersey

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 - Price \$1.00

ABSTRACT

On the basis of improved values of the energy-generation function and the opacity function that have become available in recent years, evolutionary model sequences of main-sequence stars for the mass range $\log M/M_{\odot} = 0.20$ to 0.85 have been computed. The calibration of the Hertzsprung-Russell diagram, in terms of age and mass for main-sequence B and A stars, presented in this paper was derived from the results of these evolutionary model sequence calculations.

CONTENTS

Abstract	ii
INTRODUCTION	1
ASSUMPTIONS AND CONDITIONS	2
RESULT OF HERTZSPRUNG-RUSSELL DIAGRAM CALCULATIONS	3
ZERO-AGE LINE RELATIONSHIPS	10
AGE AND EFFECTIVE-TEMPERATURE RELATIONSHIPS	15
COLOR INDICES AND THE UPPER FORTY PERCENT OF THE MAIN-SEQUENCE BAND	15
CONCLUSION	19
ACKNOWLEDGMENTS	20
References	20

STELLAR EVOLUTION I

CALIBRATION OF THE HERTZSPRUNG-RUSSELL DIAGRAM IN TERMS OF AGE AND MASS FOR MAIN-SEQUENCE B AND A STARS*

by
T. Kelsall
Goddard Space Flight Center
and
Bengt Strömgren
Institute for Advanced Study

INTRODUCTION

Early calculations of evolutionary model sequences for main-sequence B and A stars were carried out by Tayler; Kushwaha; Blackler; Henyey, LeLevier and Levee; Haselgrove and Hoyle; and Hoyle (References 1 through 6). In recent years, improved values of the energy-generation function, $\epsilon(\rho, T)$, and the opacity function, $\kappa(\rho, T)$, have become available through the efforts of Caughlan and Fowler (Reference 7); Reeves†; Cox‡; and Arking and Herring**. On this basis, Kelsall*** has computed evolutionary model sequences of main-sequence stars for the mass range $\log M/M_{\odot} = 0.20$ to 0.85. These calculations were made for six different initial compositions, X, Y and Z.

The calibration of the Hertzsprung-Russell diagram in terms of age and mass for main-sequence B and A stars presented in this paper was derived from the results of the Kelsall evolutionary model sequence calculations. In this work, the energy-generation function $\epsilon(\rho, T)$ was taken as the sum of the ϵ -values for the proton-proton process and the CNO-cycle. For the larger masses the CNO-cycle contribution is much higher than the proton-proton contribution. It was assumed that the relative abundances of the carbon, nitrogen and oxygen isotopes were those reached in equilibrium at the relevant temperature. The relative mass of N^{14} was taken as 0.6Z where Z is the relative mass of the heavy-element group (all elements except hydrogen and helium). The opacity function $\kappa(\rho, T)$ was computed according to the procedure described by Cox except that

*Supported in part by a grant from the National Science Foundation and in part by the U. S. Office of Naval Research (Contract Nonr 1858).

†Reeves, H., To be published by University of Chicago Press in *Stellar Structure, Stars and Stellar Systems*, Vol. 8, Chapt. 2 in 1965.

‡Cox, A., To be published by University of Chicago Press in *Stellar Structure, Stars and Stellar Systems*, Vol. 8, Chapt. 3, in 1965.

**Arking, A., and Herring, J., Unpublished, but summarized in *Publications of the Astronomical Society of the Pacific*, Vol. 75, no. 444, pp 226-235, June 1963.

***Kelsall, T., Unpublished report (1965).

the absorption line contribution to the opacity was taken from the investigation by Arking and Herring. For a series of combinations of X, Y and Z covering the range encountered in the stellar model calculations, tables of the opacity due to continuous absorption and scattering, as functions of the density ρ and the temperature T, were computed with the Los Alamos high-speed computer code. Corrections to allow for the line effect according to Arking and Herring were applied to these values. For the stellar model calculations, the opacity tables were stored in the computer memory, and the values of the opacity were obtained as required through computer interpolation in the tables.

ASSUMPTIONS AND CONDITIONS

For the mass range considered, all models have a convective core, and there is radiative equilibrium everywhere outside the convective core. Complete mixing of the stellar material was assumed within the convective core, and outside the convective core the effect of mixing was taken to be negligible. Following Harm and Schwarzschild (Reference 8), the $dT/dr - dP/dr$ condition for convective instability, valid in a chemically homogeneous medium, was assumed to hold in the zone with continuously varying chemical composition that surrounds the convective core.

Evolutionary tracks through the hydrogen-burning phase were calculated for $\log M/M_{\odot}$ values of 0.20, 0.25, 0.45, 0.65 and 0.85. For each mass, they were made for the six initial chemical compositions specified below:

X	Y	Z
0.60	0.38	0.02
0.60	0.37	0.03
0.60	0.36	0.04
0.70	0.28	0.02
0.70	0.27	0.03
0.70	0.26	0.04

In the choice of the initial chemical compositions, we were guided by the results of previous discussions of relative abundances in young population I stars (References 4 and 5, and 9 through 13).

The question of the initial values of X, Y and Z for the solar interior has been discussed by Osterbrock and Rogerson (Reference 14) and by Gaustad (Reference 15). Utilizing information on abundances within the heavy-element group in solar cosmic rays (Reference 16), Gaustad derived $Z/X = 0.028$ and found $X = 0.72$, $Y = 0.26$, and $Z = 0.02$. Following Gaustad in adopting $Z/X = 0.028$, Sears (Reference 17) derived $X = 0.71$, $Y = 0.27$, $Z = 0.02$, while Demarque and Percy (Reference 18) found $X = 0.70$, $Y = 0.28$, $Z = 0.020$ corresponding to $Z/X = 0.028$.

Comparison of the atmospheric abundances of metals relative to hydrogen in the sun on the one hand and young population I stars on the other (References 19 through 21) suggests that the relevant range of Z for young population I stars is 0.02 to 0.04. With regard to the relative helium

content, Y , for these stars it would be expected to be larger than, or equal to, the value for the sun (i.e., $Y \geq 0.26$). The ratio Y/Z should be smaller than, or equal to, the solar value (i.e., $Y/Z \leq 14$). Also, since we expect $Z \leq 0.04$ and $Y \geq 0.26$, we presume that $Y/Z \geq 6.5$.

For each set of values (M ; X , Y , Z) an evolutionary model sequence was computed with time steps corresponding to values of the relative hydrogen content in the convective core, X_c , as given below:

For initial $X = 0.70$: $X_c = 0.70, 0.60, 0.50, 0.40, 0.30, 0.20, 0.10$

For initial $X = 0.60$: $X_c = 0.60, 0.50, 0.40, 0.30, 0.20, 0.10$

RESULT OF HERTZSPRUNG-RUSSELL DIAGRAM CALCULATIONS

The evolutionary tracks for the last part of the hydrogen-burning phase when $X_c < 0.05$ show complications that are absent for the part covered by the calculations presented here (References 22 and 23). The tracks for very small X_c will be discussed separately by Kelsall in a future publication. In neglecting the influence of the complications in question on the age calibration, we commit errors that are quite small statistically, since, first of all the relative lifetime corresponding to $X_c < 0.05$ is only a few percent of the total main-sequence lifetime and, secondly, the deviations of evolutionary tracks in the Hertzsprung-Russell diagram obtained by smooth extrapolation beyond $X_c = 0.1$ from the true tracks are never large.

The result of the calculations of the evolutionary tracks in the Hertzsprung-Russell diagram are given in Table 1. In constructing this table, third-order polynomial interpolation between the directly computed values for mass range, $\log M/M_\odot$, equal to 0.25, 0.45, 0.65, 0.85 was utilized to produce $\log T_e$, M_{bol} , and $\log(\text{Age})$ with the interval of 0.05 in $\log M/M_\odot$. Checks against directly computed values indicate that the inaccuracies introduced through the interpolation process are at most about two units in the last decimal place given in the table. The tabular values are given to 3 decimal places in $\log T_e$ and 2 decimal places in M_{bol} in order to reduce the rounding errors in the use of the tables to an insignificant amount.

For each initial chemical composition, Table 1 gives as a function of $\log M/M_\odot$ and X_c , the corresponding stellar age reckoned from the start of hydrogen burning, the logarithm of the effective temperature T_e , the bolometric magnitude M_{bol} , and, finally, the quantity ΔM_{bol} which is defined as the difference between the bolometric magnitude on the zero-age line corresponding to T_e and the actual bolometric magnitude M_{bol} .

The numerical material for the calibration of the Hertzsprung-Russell diagram in terms of mass and age for main-sequence B and A stars is all contained in Table 1. For any of the six initial chemical compositions covered by the table, the age and the mass can be found from given values of M_{bol} and $\log T_e$ through backward interpolation. Since the network of Table 1 is sufficiently dense for linear interpolation to yield quite satisfactory accuracy the numerical process in question is simple.

Table 1

Result of Calculations of Evolutionary Tracks in Hertzsprung-Russell Diagram.

(a) $X = 0.60$ $Y = 0.38$ $Z = 0.02$

$\log \frac{M}{M_{\odot}}$	$X_c = 0.50$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.40$			
	Age (million years)	$\log T_e$	$M_{b \circ 1}$	$\Delta M_{b \circ 1}$		Age (million years)	$\log T_e$	$M_{b \circ 1}$	$\Delta M_{b \circ 1}$
0.25	129	4.007	+1.31	0.20	0.25	233	3.997	+1.24	0.41
0.30	97	4.042	+0.82	0.20	0.30	174	4.032	+0.74	0.42
0.35	73	4.076	+0.33	0.21	0.35	131	4.066	+0.25	0.44
0.40	55	4.110	-0.14	0.21	0.40	98	4.099	-0.23	0.45
0.45	41.7	4.142	-0.62	0.22	0.45	74	4.132	-0.71	0.46
0.50	31.8	4.174	-1.08	0.22	0.50	57	4.164	-1.18	0.47
0.55	24.4	4.205	-1.54	0.23	0.55	43.5	4.195	-1.64	0.48
0.60	18.9	4.235	-1.99	0.24	0.60	33.5	4.226	-2.09	0.48
0.65	14.7	4.265	-2.43	0.23	0.65	26.1	4.256	-2.54	0.47
0.70	11.5	4.294	-2.87	0.22	0.70	20.5	4.285	-2.98	0.47
0.75	9.1	4.322	-3.30	0.22	0.75	16.2	4.313	-3.42	0.48
0.80	7.3	4.349	-3.72	0.22	0.80	12.9	4.341	-3.84	0.47
0.85	5.9	4.376	-4.13	0.21	0.85	10.5	4.368	-4.26	0.47
$\log \frac{M}{M_{\odot}}$	$X_c = 0.30$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.20$			
	Age (million years)	$\log T_e$	$M_{b \circ 1}$	$\Delta M_{b \circ 1}$		Age (million years)	$\log T_e$	$M_{b \circ 1}$	$\Delta M_{b \circ 1}$
0.25	318	3.984	+1.18	0.64	0.25	387	3.970	+1.14	0.87
0.30	237	4.019	+0.68	0.66	0.30	287	4.004	+0.63	0.92
0.35	177	4.053	+0.19	0.68	0.35	214	4.038	+0.14	0.94
0.40	133	4.087	-0.30	0.69	0.40	161	4.072	-0.36	0.96
0.45	100	4.120	-0.78	0.70	0.45	121	4.105	-0.84	0.97
0.50	76	4.152	-1.26	0.72	0.50	92	4.138	-1.32	0.98
0.55	58	4.183	-1.73	0.74	0.55	70	4.169	-1.80	1.00
0.60	45.1	4.214	-2.19	0.75	0.60	54	4.201	-2.26	1.02
0.65	35.0	4.244	-2.64	0.76	0.65	42.0	4.231	-2.72	1.04
0.70	27.4	4.274	-3.08	0.75	0.70	32.9	4.261	-3.17	1.03
0.75	21.7	4.303	-3.52	0.74	0.75	26.0	4.290	-3.61	1.03
0.80	17.4	4.331	-3.95	0.73	0.80	20.8	4.318	-4.05	1.03
0.85	14.0	4.358	-4.37	0.73	0.85	16.8	4.345	-4.47	1.03
$\log \frac{M}{M_{\odot}}$	$X_c = 0.10$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.10$			
	Age (million years)	$\log T_e$	$M_{b \circ 1}$	$\Delta M_{b \circ 1}$		Age (million years)	$\log T_e$	$M_{b \circ 1}$	$\Delta M_{b \circ 1}$
0.25	442	3.956	+1.10	1.10	0.25	442	3.956	+1.10	1.10
0.30	327	3.990	+0.60	1.14	0.30	327	3.990	+0.60	1.14
0.35	244	4.024	+0.10	1.17	0.35	244	4.024	+0.10	1.17
0.40	182	4.057	-0.40	1.21	0.40	182	4.057	-0.40	1.21
0.45	137	4.091	-0.89	1.23	0.45	137	4.091	-0.89	1.23
0.50	104	4.124	-1.38	1.24	0.50	104	4.124	-1.38	1.24
0.55	79	4.156	-1.85	1.26	0.55	79	4.156	-1.85	1.26
0.60	61	4.187	-2.33	1.28	0.60	61	4.187	-2.33	1.28
0.65	47.3	4.218	-2.79	1.30	0.65	47.3	4.218	-2.79	1.30
0.70	37.1	4.248	-3.24	1.30	0.70	37.1	4.248	-3.24	1.30
0.75	29.4	4.277	-3.69	1.31	0.75	29.4	4.277	-3.69	1.31
0.80	23.5	4.305	-4.13	1.32	0.80	23.5	4.305	-4.13	1.32
0.85	19.0	4.332	-4.56	1.33	0.85	19.0	4.332	-4.56	1.33

Table 1 (continued)

(b) $X = 0.60$ $Y = 0.37$ $Z = 0.03$

$\log \frac{M}{M_{\odot}}$	$X_c = 0.50$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.40$			
	Age (million years)	$\log T_e$	$M_{b \odot 1}$	$\Delta M_{b \odot 1}$		Age (million years)	$\log T_e$	$M_{b \odot 1}$	$\Delta M_{b \odot 1}$
0.25	139	3.977	+1. ^m 49	0. ^m 19	0.25	253	3.966	+1. ^m 43	0. ^m 40
0.30	104	4.012	+0.99	0.21	0.30	188	4.002	+0.93	0.41
0.35	78	4.047	+0.50	0.21	0.35	141	4.037	+0.43	0.42
0.40	59	4.082	+0.01	0.21	0.40	106	4.071	-0.06	0.44
0.45	44.4	4.116	-0.47	0.22	0.45	80	4.105	-0.55	0.45
0.50	33.7	4.148	-0.94	0.23	0.50	60	4.138	-1.03	0.46
0.55	25.8	4.181	-1.41	0.23	0.55	46.0	4.171	-1.51	0.47
0.60	19.8	4.212	-1.87	0.23	0.60	35.3	4.202	-1.97	0.48
0.65	15.4	4.243	-2.33	0.23	0.65	27.4	4.233	-2.43	0.48
0.70	12.0	4.273	-2.78	0.23	0.70	21.4	4.263	-2.88	0.48
0.75	9.5	4.302	-3.21	0.22	0.75	16.8	4.293	-3.33	0.48
0.80	7.6	4.330	-3.64	0.22	0.80	13.4	4.322	-3.76	0.47
0.85	6.1	4.358	-4.06	0.22	0.85	10.8	4.350	-4.19	0.47
$\log \frac{M}{M_{\odot}}$	$X_c = 0.30$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.20$			
	Age (million years)	$\log T_e$	$M_{b \odot 1}$	$\Delta M_{b \odot 1}$		Age (million years)	$\log T_e$	$M_{b \odot 1}$	$\Delta M_{b \odot 1}$
0.25	347	3.953	+1. ^m 38	0. ^m 62	0.25	424	3.938	+1. ^m 35	0. ^m 86
0.30	258	3.989	+0.87	0.64	0.30	313	3.974	+0.84	0.88
0.35	192	4.024	+0.37	0.66	0.35	233	4.009	+0.33	0.91
0.40	144	4.058	-0.13	0.69	0.40	174	4.043	-0.17	0.94
0.45	108	4.092	-0.62	0.70	0.45	130	4.077	-0.67	0.96
0.50	82	4.125	-1.10	0.72	0.50	98	4.111	-1.16	0.98
0.55	62	4.158	-1.58	0.73	0.55	75	4.144	-1.64	0.99
0.60	47.6	4.190	-2.06	0.75	0.60	57	4.176	-2.12	1.01
0.65	36.8	4.221	-2.52	0.75	0.65	44.3	4.207	-2.59	1.02
0.70	28.7	4.252	-2.98	0.74	0.70	34.5	4.238	-3.05	1.02
0.75	22.6	4.282	-3.42	0.73	0.75	27.2	4.268	-3.51	1.03
0.80	18.0	4.311	-3.86	0.73	0.80	21.6	4.297	-3.95	1.03
0.85	14.5	4.339	-4.30	0.74	0.85	17.4	4.326	-4.39	1.03
$\log \frac{M}{M_{\odot}}$	$X_c = 0.10$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.10$			
	Age (million years)	$\log T_e$	$M_{b \odot 1}$	$\Delta M_{b \odot 1}$		Age (million years)	$\log T_e$	$M_{b \odot 1}$	$\Delta M_{b \odot 1}$
0.25	485	3.924	+1. ^m 33	1. ^m 07	0.25	485	3.924	+1. ^m 33	1. ^m 07
0.30	359	3.959	+0.81	1.11	0.30	359	3.959	+0.81	1.11
0.35	266	3.994	+0.30	1.15	0.35	266	3.994	+0.30	1.15
0.40	198	4.029	-0.21	1.17	0.40	198	4.029	-0.21	1.17
0.45	148	4.063	-0.71	1.20	0.45	148	4.063	-0.71	1.20
0.50	112	4.097	-1.20	1.22	0.50	112	4.097	-1.20	1.22
0.55	85	4.130	-1.69	1.24	0.55	85	4.130	-1.69	1.24
0.60	65	4.162	-2.17	1.26	0.60	65	4.162	-2.17	1.26
0.65	50	4.194	-2.65	1.28	0.65	50	4.194	-2.65	1.28
0.70	39.0	4.225	-3.12	1.29	0.70	39.0	4.225	-3.12	1.29
0.75	30.7	4.255	-3.58	1.30	0.75	30.7	4.255	-3.58	1.30
0.80	24.4	4.284	-4.03	1.31	0.80	24.4	4.284	-4.03	1.31
0.85	19.7	4.312	-4.47	1.33	0.85	19.7	4.312	-4.47	1.33

Table 1 (continued)

(c) $X = 0.60$ $Y = 0.36$ $Z = 0.04$

$\log \frac{M}{M_{\odot}}$	$X_c = 0.50$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.40$			
	Age (million years)	$\log T_e$	$M_{b\odot 1}$	$\Delta M_{b\odot 1}$		Age (million years)	$\log T_e$	$M_{b\odot 1}$	$\Delta M_{b\odot 1}$
0.25	149	3.953	+1. ^m 64	0. ^m 19	0.25	272	3.942	+1. ^m 59	0. ^m 38
0.30	111	3.989	+1.14	0.20	0.30	202	3.978	+1.08	0.41
0.35	83	4.025	+0.64	0.21	0.35	151	4.014	+0.57	0.43
0.40	62	4.060	+0.14	0.22	0.40	113	4.049	+0.07	0.44
0.45	46.9	4.095	-0.35	0.22	0.45	84	4.084	-0.42	0.44
0.50	35.5	4.129	-0.83	0.22	0.50	64	4.118	-0.91	0.46
0.55	27.0	4.162	-1.31	0.22	0.55	48.3	4.151	-1.40	0.47
0.60	20.7	4.194	-1.78	0.23	0.60	36.9	4.184	-1.87	0.48
0.65	15.9	4.226	-2.24	0.23	0.65	28.4	4.216	-2.34	0.48
0.70	12.4	4.257	-2.70	0.23	0.70	22.1	4.247	-2.80	0.48
0.75	9.8	4.287	-3.14	0.23	0.75	17.3	4.277	-3.25	0.48
0.80	7.7	4.316	-3.58	0.23	0.80	13.8	4.307	-3.69	0.48
0.85	6.2	4.344	-4.01	0.24	0.85	11.1	4.336	-4.13	0.48

$\log \frac{M}{M_{\odot}}$	$X_c = 0.30$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.20$			
	Age (million years)	$\log T_e$	$M_{b\odot 1}$	$\Delta M_{b\odot 1}$		Age (million years)	$\log T_e$	$M_{b\odot 1}$	$\Delta M_{b\odot 1}$
0.25	374	3.929	+1. ^m 55	0. ^m 59	0.25	458	3.914	+1. ^m 54	0. ^m 80
0.30	277	3.965	+1.04	0.63	0.30	339	3.950	+1.01	0.86
0.35	206	4.001	+0.53	0.66	0.35	251	3.986	+0.49	0.90
0.40	153	4.036	+0.02	0.68	0.40	187	4.021	-0.02	0.93
0.45	115	4.071	-0.48	0.69	0.45	139	4.056	-0.53	0.95
0.50	86	4.105	-0.98	0.71	0.50	104	4.090	-1.03	0.97
0.55	65	4.139	-1.47	0.72	0.55	79	4.124	-1.52	0.98
0.60	50	4.171	-1.95	0.74	0.60	60	4.157	-2.01	1.00
0.65	38.3	4.204	-2.42	0.74	0.65	46.1	4.189	-2.49	1.01
0.70	29.7	4.235	-2.89	0.74	0.70	35.8	4.221	-2.96	1.02
0.75	23.3	4.266	-3.34	0.74	0.75	28.1	4.252	-3.42	1.03
0.80	18.5	4.295	-3.79	0.75	0.80	22.3	4.281	-3.88	1.05
0.85	14.9	4.324	-4.23	0.76	0.85	17.9	4.310	-4.32	1.06

$\log \frac{M}{M_{\odot}}$	$X_c = 0.10$			
	Age (million years)	$\log T_e$	$M_{b\odot 1}$	$\Delta M_{b\odot 1}$
0.25	527	3.901	+1. ^m 51	0. ^m 99
0.30	388	3.936	+0.99	1.06
0.35	287	3.971	+0.47	1.12
0.40	213	4.006	-0.05	1.17
0.45	159	4.041	-0.56	1.19
0.50	119	4.075	-1.07	1.22
0.55	90	4.109	-1.57	1.24
0.60	68	4.142	-2.06	1.26
0.65	52	4.175	-2.55	1.28
0.70	40.5	4.207	-3.02	1.29
0.75	31.7	4.237	-3.49	1.31
0.80	25.2	4.267	-3.95	1.33
0.85	20.2	4.296	-4.40	1.35

Table 1 (continued)

(d) $X = 0.70$ $Y = 0.28$ $Z = 0.02$

$\log \frac{M}{M_{\odot}}$	$X_c = 0.60$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.50$			
	Age (million years)	$\log T_e$	$M_{b,01}$	$\Delta M_{b,01}$		Age (million years)	$\log T_e$	$M_{b,01}$	$\Delta M_{b,01}$
0.25	196	3.955	+1.86 ^m	0.16 ^m	0.25	360	3.947	+1.80 ^m	0.31 ^m
0.30	148	3.991	+1.36	0.18	0.30	270	3.983	+1.30	0.34
0.35	111	4.027	+0.87	0.18	0.35	203	4.018	+0.80	0.37
0.40	84	4.061	+0.39	0.18	0.40	153	4.052	+0.31	0.39
0.45	64	4.095	-0.09	0.18	0.45	115	4.086	-0.17	0.39
0.50	48.4	4.127	-0.56	0.19	0.50	88	4.118	-0.64	0.41
0.55	37.1	4.159	-1.03	0.19	0.55	67	4.150	-1.11	0.41
0.60	28.5	4.190	-1.48	0.20	0.60	51	4.182	-1.58	0.42
0.65	22.0	4.221	-1.94	0.20	0.65	39.5	4.212	-2.03	0.43
0.70	17.1	4.250	-2.38	0.20	0.70	30.7	4.242	-2.48	0.42
0.75	13.5	4.279	-2.82	0.20	0.75	24.0	4.271	-2.92	0.42
0.80	10.6	4.307	-3.25	0.21	0.80	19.0	4.299	-3.36	0.43
0.85	8.5	4.335	-3.67	0.20	0.85	15.2	4.327	-3.78	0.43
$X_c = 0.40$					$X_c = 0.30$				
0.25	497	3.937	+1.75 ^m	0.49 ^m	0.25	610	3.924	+1.72 ^m	0.69 ^m
0.30	371	3.972	+1.24	0.54	0.30	455	3.959	+1.21	0.74
0.35	278	4.007	+0.75	0.57	0.35	340	3.993	+0.71	0.80
0.40	208	4.041	+0.25	0.60	0.40	254	4.027	+0.21	0.83
0.45	157	4.074	-0.23	0.62	0.45	191	4.061	-0.28	0.86
0.50	119	4.107	-0.71	0.63	0.50	144	4.094	-0.77	0.88
0.55	90	4.139	-1.19	0.65	0.55	110	4.126	-1.25	0.90
0.60	69	4.171	-1.66	0.66	0.60	84	4.158	-1.72	0.92
0.65	53	4.202	-2.12	0.67	0.65	64	4.189	-2.19	0.92
0.70	41.4	4.232	-2.57	0.67	0.70	50	4.219	-2.64	0.93
0.75	32.4	4.261	-3.02	0.68	0.75	39.1	4.249	-3.10	0.94
0.80	25.6	4.290	-3.45	0.67	0.80	30.9	4.278	-3.54	0.94
0.85	20.5	4.318	-3.88	0.67	0.85	24.7	4.306	-3.97	0.95
$X_c = 0.20$					$X_c = 0.10$				
0.25	710	3.910	+1.70 ^m	0.88 ^m	0.25	790	3.896	+1.68 ^m	1.09 ^m
0.30	520	3.944	+1.18	0.97	0.20	580	3.929	+1.17	1.17
0.35	390	3.978	+0.68	1.03	0.35	432	3.963	+0.66	1.24
0.40	291	4.012	+0.18	1.07	0.40	321	3.997	+0.15	1.30
0.45	218	4.045	-0.32	1.12	0.45	240	4.030	-0.35	1.35
0.50	164	4.078	-0.81	1.14	0.50	181	4.063	-0.84	1.39
0.55	125	4.111	-1.29	1.16	0.55	137	4.096	-1.33	1.41
0.60	95	4.143	-1.77	1.17	0.60	104	4.128	-1.81	1.43
0.65	73	4.174	-2.24	1.19	0.65	80	4.160	-2.29	1.44
0.70	57	4.205	-2.71	1.21	0.70	62	4.191	-2.76	1.46
0.75	44.4	4.235	-3.16	1.21	0.75	48.5	4.221	-3.22	1.48
0.80	35.1	4.264	-3.61	1.22	0.80	38.4	4.250	-3.67	1.50
0.85	28.0	4.292	-4.05	1.24	0.85	30.6	4.278	-4.12	1.52

Table 1 (continued)

(e) $X = 0.70$ $Y = 0.27$ $Z = 0.03$

$\log \frac{M}{M_{\odot}}$	$X_c = 0.60$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.50$			
	Age (million years)	$\log T_e$	$M_{b \odot 1}$	$\Delta M_{b \odot 1}$		Age (million years)	$\log T_e$	$M_{b \odot 1}$	$\Delta M_{b \odot 1}$
0.25	211	3.924	^m +2.05	^m 0.14	0.25	390	3.915	^m +2.00	^m 0.30
0.30	159	3.961	+1.54	0.16	0.30	292	3.952	+1.49	0.32
0.35	120	3.997	+1.05	0.16	0.35	219	3.987	+0.99	0.36
0.40	90	4.032	+0.55	0.18	0.40	164	4.023	+0.49	0.37
0.45	68	4.067	+0.07	0.19	0.45	124	4.057	-0.00	0.39
0.50	52	4.101	-0.41	0.20	0.50	93	4.091	-0.49	0.41
0.55	39.3	4.134	-0.89	0.20	0.55	71	4.124	-0.97	0.42
0.60	30.1	4.166	-1.36	0.21	0.60	54	4.157	-1.44	0.42
0.65	23.1	4.198	-1.82	0.20	0.65	41.5	4.189	-1.91	0.43
0.70	17.9	4.228	-2.27	0.20	0.70	32.1	4.219	-2.37	0.43
0.75	14.0	4.258	-2.72	0.21	0.75	25.0	4.250	-2.82	0.43
0.80	11.0	4.287	-3.16	0.22	0.80	19.7	4.279	-3.26	0.44
0.85	8.8	4.316	-3.59	0.22	0.85	15.7	4.308	-3.70	0.45
$X_c = 0.40$					$X_c = 0.30$				
0.25	540	3.904	^m +1.96	^m 0.48	0.25	670	3.892	^m +1.94	^m 0.65
0.30	403	3.940	+1.45	0.53	0.30	497	3.927	+1.42	0.73
0.35	301	3.976	+0.94	0.56	0.35	370	3.962	+0.91	0.77
0.40	225	4.011	+0.44	0.59	0.40	276	3.997	+0.41	0.80
0.45	169	4.045	-0.06	0.62	0.45	207	4.032	-0.10	0.83
0.50	127	4.079	-0.55	0.64	0.50	155	4.066	-0.59	0.86
0.55	96	4.113	-1.03	0.65	0.55	117	4.099	-1.08	0.89
0.60	73	4.145	-1.51	0.67	0.60	89	4.132	-1.57	0.91
0.65	56	4.177	-1.99	0.68	0.65	68	4.164	-2.05	0.93
0.70	43.6	4.209	-2.45	0.68	0.70	53	4.196	-2.52	0.93
0.75	33.9	4.239	-2.91	0.68	0.75	40.9	4.226	-2.98	0.94
0.80	26.7	4.269	-3.36	0.69	0.80	32.2	4.256	-3.43	0.95
0.85	21.2	4.297	-3.80	0.71	0.85	25.6	4.285	-3.88	0.97
$X_c = 0.20$					$X_c = 0.10$				
0.25	770	3.878	^m +1.93	^m 0.85	0.25	860	3.864	^m +1.92	^m 1.04
0.30	570	3.912	+1.41	0.93	0.30	640	3.899	+1.40	1.10
0.35	426	3.947	+0.90	0.98	0.35	472	3.933	+0.89	1.18
0.40	317	3.982	+0.38	1.04	0.40	351	3.967	+0.37	1.25
0.45	237	4.016	-0.12	1.08	0.45	261	4.001	-0.14	1.30
0.50	177	4.050	-0.63	1.12	0.50	195	4.035	-0.65	1.35
0.55	134	4.083	-1.12	1.16	0.55	147	4.068	-1.15	1.40
0.60	102	4.116	-1.61	1.18	0.60	112	4.101	-1.65	1.44
0.65	78	4.149	-2.10	1.20	0.65	85	4.134	-2.14	1.46
0.70	60	4.181	-2.57	1.21	0.70	66	4.166	-2.62	1.48
0.75	46.6	4.212	-3.04	1.21	0.75	51	4.197	-3.09	1.49
0.80	36.6	4.242	-3.50	1.23	0.80	40.1	4.227	-3.55	1.50
0.85	29.0	4.271	-3.95	1.25	0.85	31.8	4.256	-4.01	1.52

Table 1 (continued)

(f) $X = 0.70$ $Y = 0.26$ $Z = 0.04$

$\log \frac{M}{M_{\odot}}$	$X_c = 0.60$				$\log \frac{M}{M_{\odot}}$	$X_c = 0.50$			
	Age (million years)	$\log T_e$	$M_{b \circ 1}$	$\Delta M_{b \circ 1}$		Age (million years)	$\log T_e$	$M_{b \circ 1}$	$\Delta M_{b \circ 1}$
0.25	228	3.899	^m +2.20	^m 0.15	0.25	422	3.981	^m +2.16	^m 0.29
0.30	171	3.937	+1.70	0.15	0.30	315	3.927	+1.65	0.34
0.35	128	3.974	+1.19	0.16	0.35	235	3.964	+1.14	0.35
0.40	96	4.010	+0.69	0.18	0.40	176	4.000	+0.63	0.37
0.45	72	4.045	+0.20	0.19	0.45	132	4.035	+0.14	0.38
0.50	55	4.080	-0.29	0.20	0.50	99	4.070	-0.36	0.40
0.55	41.4	4.114	-0.78	0.21	0.55	75	4.104	-0.85	0.42
0.60	31.6	4.147	-1.25	0.22	0.60	57	4.137	-1.33	0.44
0.65	24.2	4.179	-1.72	0.22	0.65	43.6	4.170	-1.81	0.45
0.70	18.6	4.211	-2.19	0.21	0.70	33.5	4.202	-2.28	0.44
0.75	14.5	4.242	-2.64	0.21	0.75	26.0	4.233	-2.74	0.44
0.80	11.4	4.272	-3.09	0.22	0.80	20.4	4.264	-3.19	0.45
0.85	9.0	4.301	-3.53	0.22	0.85	16.1	4.293	-3.64	0.46
$X_c = 0.40$					$X_c = 0.30$				
0.25	590	3.880	^m +2.13	^m 0.46	0.25	730	3.867	^m +2.12	^m 0.64
0.30	437	3.916	+1.62	0.51	0.30	540	3.903	+1.60	0.70
0.35	324	3.952	+1.10	0.55	0.35	400	3.939	+1.08	0.74
0.40	242	3.988	+0.59	0.57	0.40	297	3.974	+0.57	0.78
0.45	181	4.023	+0.09	0.60	0.45	221	4.009	+0.06	0.82
0.50	136	4.058	-0.41	0.62	0.50	166	4.044	-0.45	0.85
0.55	102	4.092	-0.91	0.65	0.55	124	4.078	-0.95	0.89
0.60	77	4.126	-1.40	0.67	0.60	94	4.112	-1.45	0.91
0.65	59	4.159	-1.88	0.67	0.65	72	4.145	-1.94	0.94
0.70	45.5	4.191	-2.35	0.68	0.70	55	4.177	-2.42	0.95
0.75	35.2	4.222	-2.82	0.68	0.75	42.7	4.209	-2.89	0.95
0.80	27.6	4.253	-3.28	0.70	0.80	33.4	4.240	-3.35	0.96
0.85	21.8	4.282	-3.73	0.72	0.85	26.4	4.269	-3.81	0.98
$X_c = 0.20$					$X_c = 0.10$				
0.25	850	3.853	^m +2.12	^m 0.81	0.25	950	3.838	^m +2.11	^m 1.01
0.30	630	3.889	+1.60	0.87	0.30	700	3.874	+1.58	1.09
0.35	462	3.924	+1.08	0.94	0.35	510	3.909	+1.06	1.16
0.40	343	3.959	+0.56	1.00	0.40	379	3.944	+0.54	1.22
0.45	255	3.994	+0.04	1.04	0.45	281	3.979	+0.02	1.27
0.50	190	4.029	-0.47	1.08	0.50	209	4.014	-0.50	1.31
0.55	143	4.063	-0.98	1.12	0.55	157	4.048	-1.01	1.36
0.60	108	4.096	-1.48	1.16	0.60	119	4.081	-1.51	1.41
0.65	82	4.129	-1.98	1.20	0.65	90	4.114	-2.01	1.45
0.70	63	4.161	-2.47	1.23	0.70	69	4.146	-2.50	1.48
0.75	48.6	4.193	-2.95	1.25	0.75	53	4.178	-2.99	1.51
0.80	38.0	4.224	-3.42	1.26	0.80	41.8	4.209	-3.47	1.53
0.85	30.1	4.254	-3.87	1.27	0.85	33.0	4.239	-3.93	1.54

On the basis of the numerical values given in Table 1, diagrams giving curves of equal mass and equal age in a $\log T_e - M_{bol}$ plane have been constructed. Figures 1, 2, and 3 show the diagrams for the initial chemical compositions (0.70, 0.27, 0.03), (0.60, 0.37, 0.03), and (0.60, 0.36, 0.04).

ZERO-AGE LINE RELATIONSHIPS

The following discussion is based on the numerical data given in Table 1. Consider, first, the location of the zero-age line in the Hertzsprung-Russell diagram. Table 2 gives the zero-age lines through the tabulation of M_{bol} as a function of $\log T_e$ for the six different initial chemical compositions in question. Table 3 presents the zero-age line material arranged according to the relative hydrogen content X and the helium-metal ratio Y/Z . Comparison of the two pairs of columns with equal Y/Z and different X shows, that to a high degree of approximation, the location of the zero-age line is a function of Y/Z only, independent of X , throughout the range of effective temperatures in question.

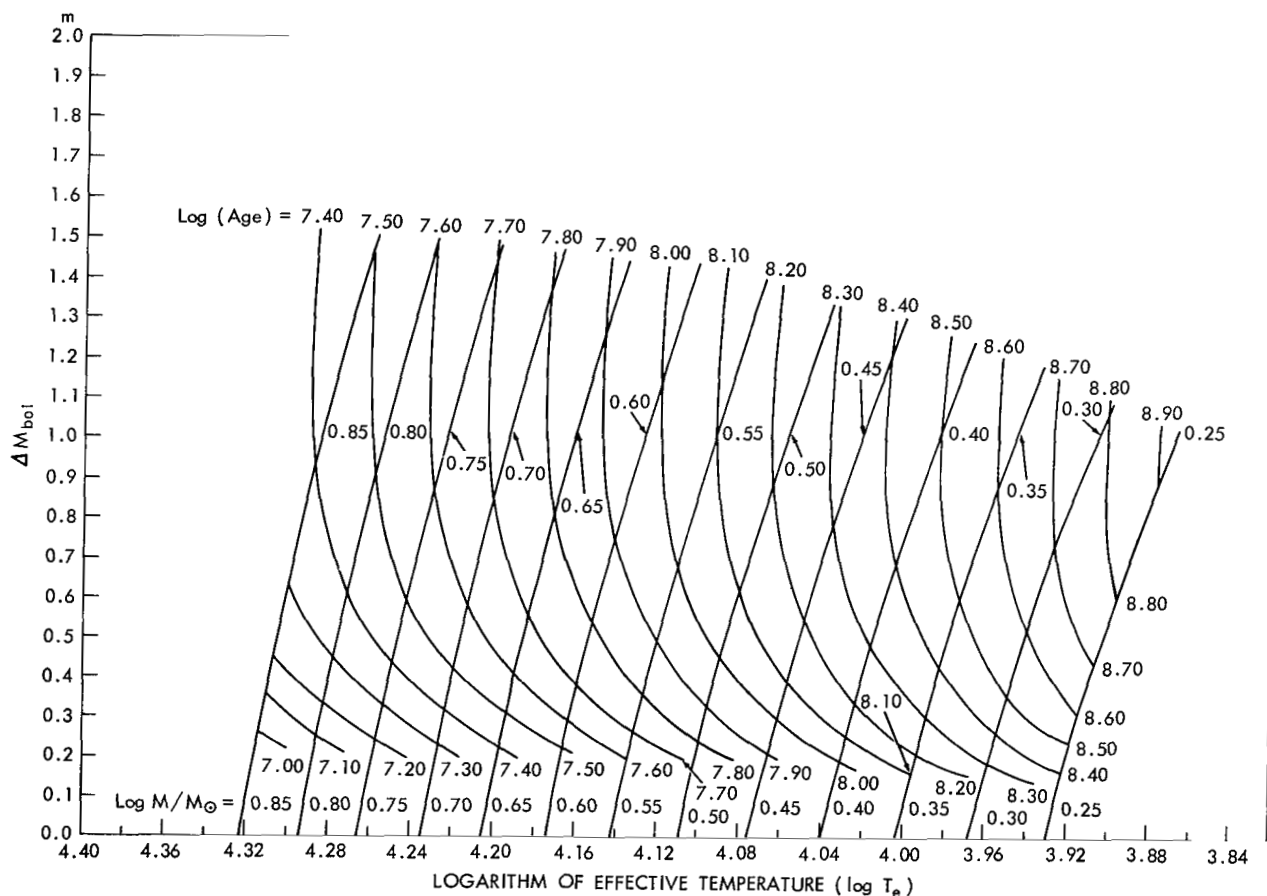


Figure 1—Curves of constant mass and constant age in a $M_{bol} - \log T_e$ plane (where $X = 0.70$, $Y = 0.27$, and $Z = 0.03$). The upper limit of the calibrated region corresponds to $X_c = 0.1$. The region of hydrogen burning extends $0.2 - 0.3$ beyond this limit. Curves of constant mass are shown for $\log M/M_\odot$ equal to 0.25, 0.30, ..., 0.85. Curves of constant age are shown for $\log \text{Age}$ (years) equal to 7.00, 7.10, ..., 8.90.

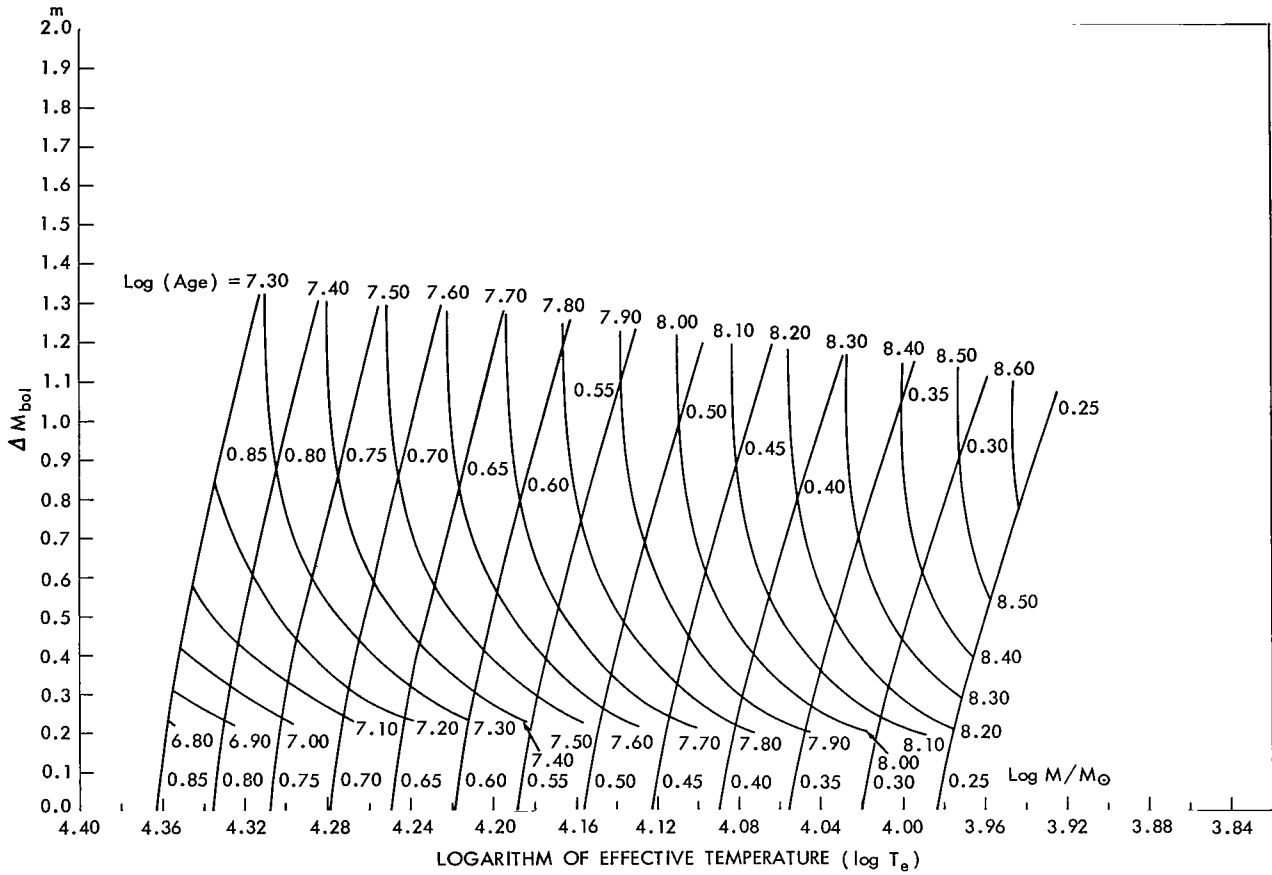


Figure 2—Curves of constant mass and constant age in a M_{bol} - $\log T_e$ plane (where $X = 0.60$, $Y = 0.37$, and $Z = 0.03$). The upper limit of the calibrated region corresponds to $X_c = 0.1$. The region of hydrogen burning extends $0.2 - 0.3$ beyond this limit. Curves of constant mass are shown for $\log M/M_\odot$ equal to $0.25, 0.30, \dots, 0.85$. Curves of constant age are shown for $\log \text{Age}$ (years) equal to $6.80, 6.90, \dots, 8.60$.

The last column of Table 3 contains the observed zero-age line derived in the form of a $\log T_e - M_{bol}$ relation from the observed relation between color index and M_v with a temperature scale and bolometric corrections obtained on the basis of model-atmosphere calculations. As stated above, we expect Y/Z to fall in the range 6.5 to 14. Comparison of the observed and the computed $\log T_e - M_{bol}$ relations, as presented in Table 3, suggests that the representative value of Y/Z for young population I is closer to the lower limit 6.5 than to the upper limit. However, the variation of the location of the zero-age line with Y/Z is not large, and Y/Z cannot be very accurately determined in this fashion. Indeed, if we choose the value $Y/Z = 9$ to represent the whole range of plausible Y/Z values, then we predict (without adjustment of any parameter) a zero-age line that agrees with the observed zero-age line, practically within the uncertainty of the latter; and the maximum uncertainty in the prediction due to the possible deviation of the actual Y/Z value from the chosen value is only about $0^m.2$. In this fashion we obtain a test of the computed zero-age models. The result is quite satisfactory.

Next, the mass-luminosity relation on the zero-age line for the different initial chemical compositions in question is considered. Table 4 gives M_{bol} on the zero-age line as a function of $\log M/M_{\odot}$ for six different chemical compositions that are arranged according to X and Y/Z . Whereas the location of the zero-age line in the Hertzsprung-Russell diagram is insensitive to X and depends on Y/Z , the zero-age mass-luminosity relation is more sensitive to X than to Y/Z .

Sirius A is close to the zero-age line. With the values of M_{bol} and $\log M/M_{\odot}$ given by Harris, Strand and Worley (Reference 24), we find through projection on the zero-age line along the relevant evolutionary track given by Table 1 that the zero-age value of M_{bol} corresponding to the mass of Sirius A ($\log M/M_{\odot} = 0.33$) is 1.2 . With $Y/Z = 9.0$, we then find from Table 4 a value of X equal to 0.68, while the assumption that $Y/Z = 6.5$ gives $X = 0.64$.

For a number of spectroscopic binaries for which the mass, the effective temperature and the bolometric magnitude are known with good, or fair accuracy values of X have been derived through

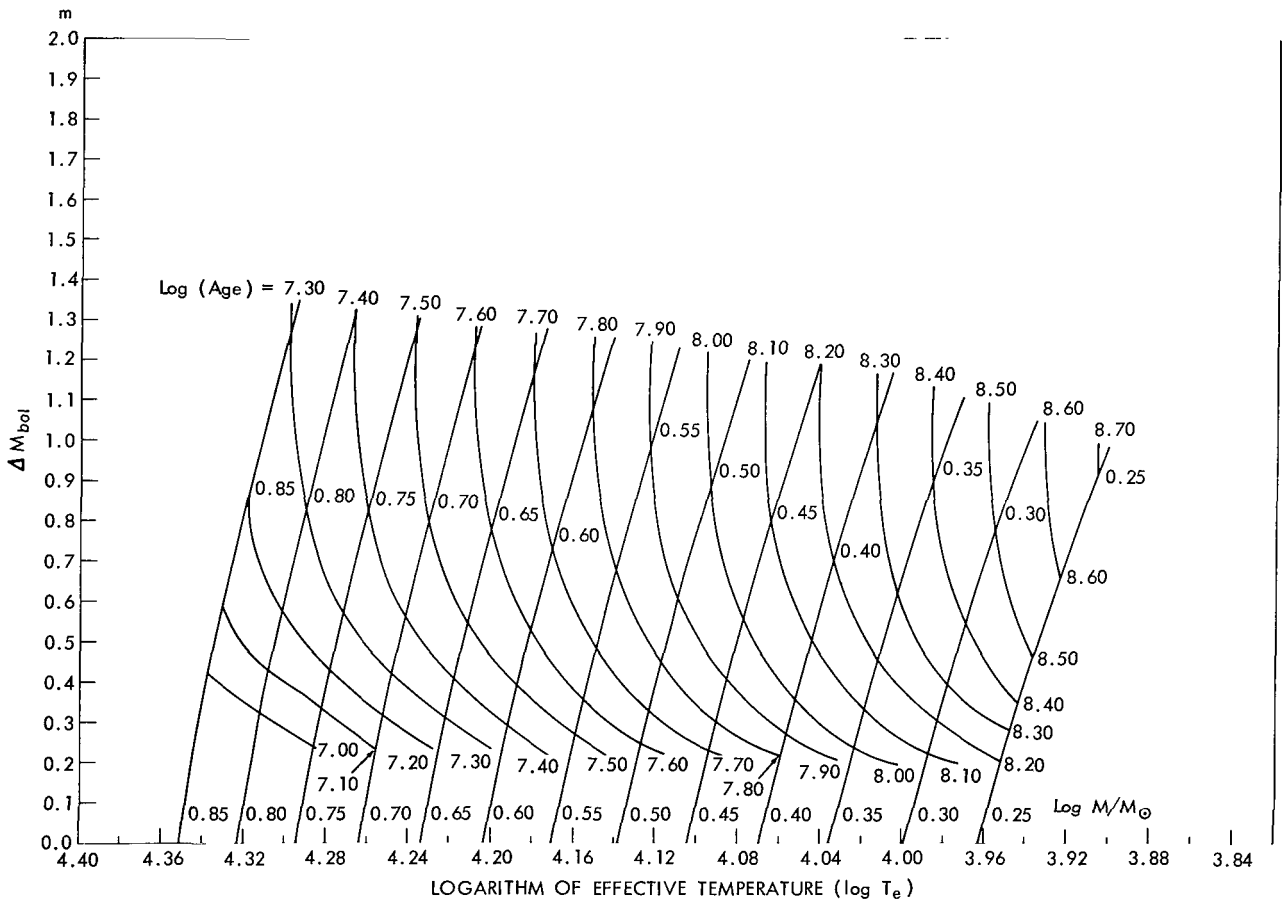


Figure 3—Curves of constant mass and constant age in a $M_{\text{bol}} - \log T_e$ plane (where $X = 0.60$, $Y = 0.36$, and $Z = 0.04$). The upper limit of the calibrated region correspond to $X_c = 0.1$. The region of hydrogen burning extends $0.2 - 0.3$ beyond this limit. Curves of constant mass are shown for $\log M/M_{\odot}$ equal to 0.25, 0.30, . . . , 0.85. Curves of constant age are shown for $\log \text{Age}$ (years) equal to 7.00, 7.10, . . . , 8.70.

Table 2
Zero-age Lines for Six Different Initial Chemical Compositions

Logarithm of Effective Temperature, $\log T_e$	Bolometric Magnitude, M_{bol}					
	X = 0.60	X = 0.60	X = 0.60	X = 0.70	X = 0.70	X = 0.70
	Y = 0.38 Z = 0.02	Y = 0.37 Z = 0.03	Y = 0.36 Z = 0.04	Y = 0.28 Z = 0.02	Y = 0.27 Z = 0.03	Y = 0.26 Z = 0.04
3.90					+2.49 ^m	+2.34 ^m
3.91			+2.39 ^m	+2.58 ^m	+2.36	+2.21
3.92			+2.26	+2.46	+2.24	+2.08
3.93		+2.31 ^m	+2.13	+2.33	+2.11	+1.95
3.94		+2.18	+2.00	+2.20	+1.98	+1.81
3.95	+2.28 ^m	+2.04	+1.87	+2.07	+1.84	+1.68
3.96	+2.15	+1.91	+1.74	+1.94	+1.71	+1.55
3.97	+2.01	+1.77	+1.60	+1.81	+1.58	+1.41
3.98	+1.88	+1.64	+1.47	+1.68	+1.45	+1.27
3.99	+1.74	+1.50	+1.33	+1.55	+1.31	+1.13
4.00	+1.61	+1.37	+1.20	+1.41	+1.17	+1.00
4.01	+1.47	+1.23	+1.06	+1.28	+1.04	+0.87
4.02	+1.33	+1.09	+0.92	+1.14	+0.90	+0.73
4.03	+1.19	+0.95	+0.78	+1.00	+0.76	+0.59
4.04	+1.05	+0.81	+0.64	+0.87	+0.63	+0.46
4.05	+0.91	+0.67	+0.50	+0.73	+0.49	+0.32
4.06	+0.77	+0.53	+0.36	+0.59	+0.35	+0.18
4.07	+0.63	+0.39	+0.22	+0.44	+0.22	+0.04
4.08	+0.49	+0.25	+0.08	+0.30	+0.08	-0.09
4.09	+0.35	+0.11	-0.06	+0.16	-0.06	-0.23
4.10	+0.20	-0.03	-0.20	+0.02	-0.20	-0.37
4.11	+0.06	-0.17	-0.34	-0.12	-0.34	-0.51
4.12	-0.08	-0.31	-0.48	-0.26	-0.49	-0.65
4.13	-0.22	-0.45	-0.62	-0.41	-0.63	-0.79
4.14	-0.37	-0.60	-0.77	-0.56	-0.77	-0.93
4.15	-0.51	-0.74	-0.91	-0.70	-0.92	-1.08
4.16	-0.65	-0.88	-1.06	-0.85	-1.06	-1.22
4.17	-0.80	-1.03	-1.20	-0.99	-1.20	-1.36
4.18	-0.94	-1.17	-1.34	-1.13	-1.35	-1.51
4.19	-1.09	-1.31	-1.49	-1.28	-1.50	-1.66
4.20	-1.23	-1.46	-1.63	-1.42	-1.65	-1.81
4.21	-1.38	-1.61	-1.77	-1.57	-1.80	-1.96
4.22	-1.52	-1.76	-1.92	-1.72	-1.95	-2.11
4.23	-1.67	-1.91	-2.07	-1.87	-2.10	-2.26
4.24	-1.82	-2.06	-2.22	-2.03	-2.24	-2.40
4.25	-1.97	-2.21	-2.37	-2.18	-2.39	-2.54
4.26	-2.13	-2.36	-2.52	-2.33	-2.54	-2.69
4.27	-2.28	-2.51	-2.67	-2.48	-2.68	-2.84
4.28	-2.43	-2.66	-2.81	-2.63	-2.83	-2.98
4.29	-2.59	-2.81	-2.96	-2.78	-2.98	-3.13
4.30	-2.74	-2.96	-3.11	-2.93	-3.13	-3.29
4.31	-2.89	-3.11	-3.26	-3.08	-3.28	-3.44
4.32	-3.05	-3.26	-3.41	-3.24	-3.44	
4.33	-3.20	-3.42	-3.56	-3.39		
4.34	-3.36	-3.57	-3.71	-3.55		
4.35	-3.51	-3.72	-3.86			

Table 3

Zero-age Lines for Different Values of Relative Hydrogen
Content X and Helium-to-Metal Ratio Y/Z

Logarithm of Effective Temperature, $\log T_e$	Bolometric Magnitude, M_{bol}						Observational zero-age line*
	X = 0.60 Y/Z = 19.0	X = 0.60 Y/Z = 14.0	X = 0.70 Y/Z = 14.0	X = 0.60 Y/Z = 9.0	X = 0.70 Y/Z = 9.0	X = 0.70 Y/Z = 6.5	
3.97	+2. ^m 01	+1. ^m 83	+1. ^m 81	+1. ^m 60	+1. ^m 58	+1. ^m 41	+1. ^m 7
4.02	+1.33	+1.15	+1.14	+0.92	+0.90	+0.73	+0.8
4.07	+0.63	+0.45	+0.44	+0.22	+0.22	+0.04	0.0
4.12	-0.08	-0.25	-0.26	-0.48	-0.49	-0.65	-0.7
4.17	-0.80	-0.97	-0.99	-1.20	-1.20	-1.36	-1.4
4.22	-1.52	-1.70	-1.72	-1.92	-1.95	-2.11	-2.1
4.27	-2.28	-2.45	-2.48	-2.67	-2.68	-2.84	-2.8
4.32	-3.05	-3.21	-3.24	-3.41	-3.44	-3.60	-3.5

*See Reference 26, p. 532.

Table 4

Mass-Luminosity Relation on the Zero-age Line for Different Values of
Relative Hydrogen Content X and Helium-to-Metal Ratio Y/Z

Mass Range, $\log \frac{M}{M_\odot}$	Bolometric Magnitude, M_{bol}					
	X = 0.60 Y/Z = 19.0	X = 0.60 Y/Z = 14.0	X = 0.70 Y/Z = 14.0	X = 0.60 Y/Z = 9.0	X = 0.70 Y/Z = 9.0	X = 0.70 Y/Z = 6.5
0.25	+1. ^m 40	+1. ^m 53	+1. ^m 93	+1. ^m 71	+2. ^m 11	+2. ^m 26
0.35	+0.43	+0.55	+0.95	+0.71	+1.12	+1.26
0.45	-0.51	-0.41	0.00	-0.26	+0.15	+0.28
0.55	-1.42	-1.33	-0.93	-1.21	-0.80	-0.68
0.65	-2.31	-2.24	-1.83	-2.13	-1.72	-1.62
0.75	-3.17	-3.10	-2.70	-3.02	-2.61	-2.53
0.85	-4.00	-3.95	-3.55	-3.87	-3.47	-3.41

the procedure just indicated. The results are to be discussed in a separate investigation. Here we wish to mention that the X values generally fall in the range 0.6-0.7, although X values between 0.5 and 0.6 do occur. In this connection we refer to results obtained by Eggen (Reference 12) for F and G type visual binaries (outside the range of the calibration presented here) in the Hyades. Eggen's results suggest a lower X value for the Hyades, around X = 0.5. In this

connection it should be noted that our age and mass calibration can be extrapolated without serious loss of accuracy to X -values as low as about 0.5.

AGE AND EFFECTIVE-TEMPERATURE RELATIONSHIPS

While Table 1 gives $\log T_e$, M_{bol} , and stellar age with the arguments $\log M/M_\odot$ and X_c , Table 5 presents equivalent information in the form of a tabulation of $\log T_e$ and ΔM_{bol} with the arguments $\log(\text{Age})$ and X_c . Thus, Table 1 contains the data for the construction of curves of equal mass in the Hertzsprung-Russell diagram, whereas Table 5 is convenient in drawing curves of equal age. We have chosen to tabulate $\log(\text{Age})$ rather than Age in Table 5 because interpolation is then somewhat more convenient except in the immediate neighborhood of the zero-age line.

Figures 1, 2 and 3 illustrate the well-known fact that age determination from $\log T_e$ and M_{bol} is more accurate in the upper part of the main-sequence band than in the lower, because the distances between lines of equal age generally increase with distance from the zero-age line. Figures 1, 2 and 3 also show that the curves of equal age are very nearly straight vertical lines in the upper 40 percent of the main-sequence band (i.e., when ΔM_{bol} is larger than 0.6 times the width of the main-sequence band at the effective temperature in question). We shall make use of this very convenient feature of the age-calibration curves in the following discussions of age determination for stars in the upper 40-percent of the main-sequence band.

Inspection of the $\log T_e$ columns of Table 5 shows that the differences between the $\log T_e$ values for the same value of $\log(\text{Age})$ (and the same initial chemical composition) but different X_c values average only a few units in the third decimal place when ΔM_{bol} is larger than 0.6 times the main-sequence width. Table 6 gives values for $\log T_e$ as a function of $\log(\text{Age})$ which are valid to a very good approximation in the upper 40-percent of the main-sequence band. The values of $\log(\text{Age})$ are given for three different compositions, namely, (0.70, 0.27, 0.03), (0.60, 0.37, 0.03) and (0.60, 0.36, 0.04). Comparison of the first two $\log T_e$ columns shows the effect upon the resulting age of a change in the assumed relative hydrogen content X , while the two last columns serve the analogous purpose for the case of change in the relative heavy-element content Z .

COLOR INDICES AND THE UPPER FORTY PERCENT OF THE MAIN-SEQUENCE BAND

When the temperature scale valid for stars in the upper 40-percent of the main-sequence band is known, Table 6 can be converted into a table giving $\log(\text{Age})$ as a function of an intrinsic color index. For the spectral range B2 to B8 the relation between T_e and the intrinsic color index $(u - b)_0$ of the system of photoelectric uvby photometry (References 21 and 25) has been derived on the basis of model-atmosphere calculations (Reference 26). The relation between the intrinsic color indices $(U - B)_0$ and $(u - b)_0$ is known from observations; hence, the stellar age can be tabulated (again for the upper 40-percent of the main-sequence band) as a function of $(U - B)_0$ or $(u - b)_0$. Table 7 gives the relation between $(U - B)_0$, $(u - b)_0$ and the age for the initial chemical composition (0.70, 0.27, 0.03).

Table 5

Effective Temperature and Difference of Bolometric Magnitude as
Related to Age and Convective-Core Hydrogen Content

(a) $X = 0.60$, $Y = 0.38$, $Z = 0.02$

log Age (years)	$X_c = 0.50$		$X_c = 0.40$		$X_c = 0.30$		$X_c = 0.20$		$X_c = 0.10$	
	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}
8.70							3.940	0 ^m .83	3.941	1 ^m .08
8.60					3.958	0 ^m .61	3.967	0.87	3.968	1.11
8.60			3.960	0 ^m .38	3.985	0.64	3.993	0.90	3.994	1.14
8.40			3.988	0.40	4.012	0.66	4.020	0.93	4.021	1.17
8.30	3.953	0 ^m .15	4.016	0.42	4.039	0.67	4.046	0.95	4.047	1.20
8.20	3.981	0.18	4.043	0.43	4.066	0.68	4.073	0.96	4.074	1.22
8.10	4.010	0.20	4.070	0.44	4.093	0.69	4.100	0.97	4.101	1.23
8.00	4.038	0.20	4.097	0.45	4.121	0.70	4.127	0.98	4.128	1.24
7.90	4.065	0.21	4.124	0.46	4.148	0.72	4.154	1.00	4.156	1.26
7.80	4.093	0.21	4.151	0.47	4.175	0.74	4.182	1.01	4.183	1.28
7.70	4.121	0.21	4.179	0.47	4.202	0.75	4.210	1.03	4.211	1.30
7.60	4.148	0.22	4.206	0.48	4.229	0.75	4.237	1.04	4.239	1.30
7.50	4.175	0.22	4.233	0.48	4.256	0.75	4.265	1.03	4.268	1.31
7.40	4.202	0.23	4.260	0.47	4.284	0.74	4.294	1.03	4.297	1.32
7.30	4.229	0.24	4.288	0.47	4.313	0.74	4.323	1.03	4.326	1.33
7.20	4.256	0.23	4.316	0.48	4.343	0.73	4.352	1.03	4.355	1.34
7.10	4.284	0.22	4.344	0.47						
7.00	4.311	0.22	4.373	0.47						
6.90	4.339	0.22								
6.80	4.368	0.21								

(b) $X = 0.60$, $Y = 0.37$, $Z = 0.03$

8.80							3.892	0 ^m .79	3.894	1 ^m .03
8.70					3.909	0 ^m .61	3.919	0.83	3.920	1.06
8.60					3.936	0.62	3.946	0.86	3.947	1.10
8.50			3.939	0 ^m .38	3.964	0.62	3.973	0.88	3.974	1.13
8.40			3.967	0.40	3.992	0.64	4.000	0.90	4.001	1.15
8.30	3.931	0 ^m .19	3.995	0.41	4.019	0.66	4.027	0.93	4.028	1.17
8.20	3.960	0.19	4.023	0.42	4.046	0.68	4.054	0.95	4.055	1.19
8.10	3.989	0.20	4.050	0.43	4.074	0.69	4.081	0.96	4.083	1.21
8.00	4.017	0.21	4.078	0.44	4.101	0.71	4.109	0.98	4.110	1.23
7.90	4.045	0.21	4.105	0.45	4.128	0.72	4.137	0.99	4.138	1.24
7.80	4.073	0.21	4.133	0.46	4.156	0.73	4.164	1.00	4.166	1.26
7.70	4.101	0.22	4.161	0.47	4.184	0.74	4.192	1.02	4.194	1.28
7.60	4.129	0.22	4.188	0.48	4.212	0.75	4.220	1.02	4.222	1.29
7.50	4.156	0.23	4.215	0.48	4.240	0.74	4.249	1.02	4.251	1.30
7.40	4.184	0.23	4.243	0.48	4.269	0.73	4.278	1.03	4.280	1.31
7.30	4.211	0.23	4.272	0.48	4.298	0.73	4.308	1.03	4.310	1.33
7.20	4.239	0.23	4.301	0.48	4.328	0.73	4.339	1.03		
7.10	4.267	0.23	4.330	0.47	4.357	0.74				
7.00	4.296	0.22	4.360	0.47						
6.90	4.324	0.22								
6.80	4.354	0.22								

Table 5 (continued)

(c) $X = 0.60$, $Y = 0.36$, $Z = 0.04$

log Age (years)	$X_c = 0.50$		$X_c = 0.40$		$X_c = 0.30$		$X_c = 0.20$		$X_c = 0.10$	
	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}
8.80							3.877	0.72	3.881	0.94
8.70					3.894	0.54	3.904	0.78	3.907	1.00
8.60			3.894	0.34	3.922	0.58	3.931	0.83	3.933	1.05
8.50			3.923	0.36	3.949	0.61	3.958	0.87	3.960	1.10
8.40			3.952	0.39	3.977	0.64	3.986	0.90	3.987	1.14
8.30	3.916	0.16	3.980	0.41	4.005	0.66	4.013	0.92	4.014	1.17
8.20	3.945	0.18	4.008	0.43	4.032	0.68	4.041	0.94	4.041	1.19
8.10	3.973	0.20	4.036	0.44	4.060	0.69	4.068	0.96	4.068	1.21
8.00	4.002	0.20	4.064	0.44	4.087	0.70	4.095	0.97	4.096	1.23
7.90	4.030	0.21	4.091	0.45	4.115	0.71	4.123	0.98	4.123	1.25
7.80	4.058	0.22	4.119	0.46	4.143	0.72	4.151	1.00	4.151	1.27
7.70	4.087	0.22	4.147	0.47	4.171	0.74	4.179	1.01	4.180	1.28
7.60	4.115	0.22	4.175	0.48	4.199	0.74	4.208	1.02	4.209	1.29
7.50	4.143	0.22	4.203	0.48	4.227	0.74	4.237	1.03	4.237	1.31
7.40	4.171	0.22	4.231	0.48	4.256	0.74	4.266	1.04	4.267	1.33
7.30	4.199	0.23	4.260	0.48	4.286	0.75	4.296	1.05	4.298	1.35
7.20	4.227	0.23	4.289	0.48	4.316	0.76	4.326	1.07		
7.10	4.255	0.23	4.319	0.48						
7.00	4.284	0.23	4.350	0.48						
6.90	4.313	0.23								
6.80	4.343	0.24								

(d) $X = 0.70$, $Y = 0.28$, $Z = 0.02$

log Age (years)	$X_c = 0.60$		$X_c = 0.50$		$X_c = 0.40$		$X_c = 0.30$		$X_c = 0.20$		$X_c = 0.10$	
	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}	log T_e	ΔM_{bol}
8.90											3.895	1.09
8.80					3.907	0.46	3.920	0.68	3.923	0.91	3.920	1.15
8.70			3.904	0.28	3.936	0.49	3.948	0.72	3.949	0.98	3.946	1.21
8.60			3.934	0.30	3.964	0.53	3.975	0.77	3.976	1.03	3.972	1.26
8.50			3.963	0.32	3.991	0.56	4.002	0.81	4.002	1.06	3.999	1.30
8.40	3.921	0.14	3.992	0.35	4.019	0.58	4.029	0.83	4.029	1.10	4.025	1.34
8.30	3.952	0.16	4.020	0.37	4.046	0.60	4.056	0.85	4.055	1.13	4.052	1.37
8.20	3.982	0.18	4.048	0.39	4.073	0.62	4.083	0.87	4.082	1.14	4.079	1.40
8.10	4.011	0.18	4.076	0.39	4.100	0.63	4.110	0.89	4.110	1.16	4.106	1.42
8.00	4.040	0.18	4.103	0.40	4.127	0.64	4.137	0.90	4.137	1.17	4.133	1.43
7.90	4.068	0.18	4.130	0.41	4.155	0.65	4.164	0.91	4.164	1.18	4.161	1.44
7.80	4.096	0.18	4.157	0.41	4.182	0.66	4.192	0.92	4.192	1.20	4.189	1.46
7.70	4.123	0.19	4.184	0.42	4.209	0.67	4.219	0.93	4.220	1.21	4.217	1.48
7.60	4.151	0.19	4.211	0.42	4.236	0.67	4.247	0.94	4.248	1.21	4.246	1.50
7.50	4.178	0.20	4.238	0.42	4.264	0.68	4.275	0.94	4.277	1.23	4.274	1.52
7.40	4.205	0.20	4.266	0.42	4.292	0.67	4.304	0.95	4.305	1.25	4.303	1.54
7.30	4.233	0.20	4.294	0.43	4.321	0.67	4.332	0.95				
7.20	4.260	0.20	4.322	0.43								
7.10	4.287	0.20										
7.00	4.315	0.21										
6.90	4.343	0.20										

Table 5 (continued)

(e) $X = 0.70$, $Y = 0.27$, $Z = 0.03$

log Age (years)	$X_c = 0.60$		$X_c = 0.50$		$X_c = 0.40$		$X_c = 0.30$		$X_c = 0.20$		$X_c = 0.10$	
	log T_e	ΔM_{bo1}	log T_e	ΔM_{bo1}	log T_e	ΔM_{bo1}	log T_e	ΔM_{bo1}	log T_e	ΔM_{bo1}	log T_e	ΔM_{bo1}
8.90									3.875	0.84^m	3.874	1.06^m
8.80							3.899	0.67^m	3.901	0.90	3.900	1.10
8.70			3.882	0.27^m	3.913	0.49^m	3.926	0.73	3.928	0.95	3.926	1.16
8.60			3.912	0.30	3.941	0.53	3.953	0.76	3.955	0.99	3.953	1.22
8.50	3.868	0.12^m	3.941	0.31	3.970	0.56	3.981	0.79	3.982	1.04	3.979	1.27
8.40	3.900	0.13	3.970	0.34	3.997	0.58	4.008	0.81	4.009	1.07	4.006	1.31
8.30	3.931	0.14	3.999	0.36	4.025	0.60	4.036	0.83	4.036	1.10	4.033	1.35
8.20	3.961	0.16	4.027	0.37	4.053	0.62	4.064	0.86	4.063	1.13	4.060	1.39
8.10	3.991	0.16	4.055	0.39	4.080	0.64	4.091	0.88	4.090	1.16	4.087	1.43
8.00	4.019	0.17	4.083	0.41	4.108	0.65	4.118	0.90	4.118	1.18	4.115	1.45
7.90	4.048	0.18	4.110	0.42	4.136	0.67	4.146	0.92	4.146	1.20	4.143	1.47
7.80	4.076	0.19	4.138	0.42	4.163	0.68	4.174	0.93	4.174	1.21	4.171	1.48
7.70	4.105	0.20	4.166	0.42	4.191	0.68	4.202	0.93	4.203	1.21	4.199	1.49
7.60	4.133	0.20	4.194	0.43	4.220	0.68	4.230	0.94	4.231	1.22	4.228	1.50
7.50	4.160	0.21	4.221	0.43	4.240	0.68	4.258	0.95	4.260	1.24	4.257	1.52
7.40	4.188	0.20	4.249	0.43	4.276	0.69	4.287	0.97	4.289	1.26	4.286	1.53
7.30	4.215	0.20	4.278	0.44	4.304	0.71						
7.20	4.243	0.20	4.307	0.45								
7.10	4.271	0.21										
7.00	4.299	0.22										
6.90	4.327	0.22										

(f) $X = 0.70$, $Y = 0.26$, $Z = 0.04$

8.90							3.856	0.62^m	3.861	0.82^m	3.858	1.06^m
8.80					3.871	0.45^m	3.884	0.67	3.888	0.87	3.885	1.11
8.70			3.869	0.27^m	3.899	0.49	3.912	0.71	3.915	0.92	3.912	1.16
8.60			3.898	0.30	3.927	0.52	3.940	0.74	3.942	0.97	3.938	1.21
8.50	3.855	0.12^m	3.926	0.34	3.955	0.55	3.967	0.77	3.969	1.01	3.965	1.25
8.40	3.886	0.14	3.955	0.35	3.983	0.57	3.994	0.80	3.996	1.04	3.992	1.29
8.30	3.916	0.15	3.984	0.36	4.011	0.59	4.021	0.83	4.023	1.07	4.020	1.32
8.20	3.946	0.15	4.013	0.37	4.039	0.61	4.049	0.86	4.051	1.11	4.047	1.36
8.10	3.976	0.16	4.041	0.38	4.067	0.63	4.077	0.89	4.078	1.14	4.074	1.40
8.00	4.005	0.18	4.069	0.40	4.095	0.65	4.105	0.91	4.105	1.17	4.102	1.43
7.90	4.033	0.19	4.097	0.42	4.123	0.67	4.133	0.93	4.133	1.20	4.130	1.46
7.80	4.062	0.19	4.125	0.43	4.151	0.67	4.161	0.94	4.161	1.23	4.158	1.49
7.70	4.090	0.20	4.153	0.44	4.179	0.68	4.189	0.95	4.189	1.25	4.186	1.52
7.60	4.119	0.21	4.181	0.45	4.207	0.68	4.218	0.95	4.218	1.26	4.215	1.53
7.50	4.147	0.22	4.209	0.44	4.236	0.69	4.247	0.96	4.247	1.27	4.244	1.54
7.40	4.174	0.22	4.237	0.44	4.265	0.71	4.276	0.98	4.277	1.28	4.273	1.55
7.30	4.202	0.21	4.266	0.44	4.293	0.73						
7.20	4.231	0.21	4.295	0.45								
7.10	4.259	0.22										
7.00	4.288	0.22										

Table 6

Relation Between Age and Effective Temperature.*

log Age (years)	log T _e		
	X = 0.70	X = 0.60	X = 0.60
	Y = 0.27	Y = 0.37	Y = 0.36
	Z = 0.03	Z = 0.03	Z = 0.04
8.80	3.900	3.893	3.879
8.70	3.927	3.920	3.906
8.60	3.954	3.947	3.932
8.50	3.981	3.974	3.959
8.40	4.008	4.001	3.987
8.30	4.035	4.028	4.014
8.20	4.062	4.055	4.041
8.10	4.089	4.082	4.068
8.00	4.117	4.110	4.096
7.90	4.145	4.138	4.123
7.80	4.173	4.165	4.151
7.70	4.201	4.193	4.180
7.60	4.230	4.221	4.209
7.50	4.258	4.250	4.237
7.40	4.287	4.279	4.267
7.30	4.316	4.309	4.297

*Valid for the upper 40 percent of the main-sequence band (ΔM_{bol} larger than about 1 magnitude), where the relation is found to be practically independent of the absolute magnitude.

Table 7

Relation Between Color Indices (U-B)₀ and (u-b)₀ for the Upper 40 Percent of the Main-Sequence Band.*

(U-B) ₀	(u-b) ₀	log T _e	log Age** (years)
-0.80	+0.16	4.329	7.26
-0.70	+0.31	4.275	7.44
-0.60	+0.46	4.222	7.63
-0.50	+0.62	4.172	7.80
-0.40	+0.79	4.128	7.96
-0.30	+0.97	4.087	8.11

* See Reference 26, p. 532.

**Age given corresponds to X = 0.70, Y = 0.27, and Z = 0.03.

It is clear that Tables 6 or 7 can be used for age determination of clusters and associations that contain stars which have evolved into the upper 40-percent of the main-sequence band when these stars are in the range of T_e covered by the tables. We proceed to discuss the case of age determination for field stars of spectral type B on the basis of photoelectric UB_V and H β photometry (References 27 and 28).

When the location of a star in Crawford's (U - B)₀ - β diagram for B stars (Reference 27) is known the effective temperature T_e and the bolometric magnitude M_{bol} can be evaluated, and the age can be found from Table 1 or Table 5. If the location in the (U - B)₀ - β diagram is such that the star is in the upper 40-percent part of the main-sequence band, then the corresponding age is practically independent of β , and it can be found from (U - B)₀ with the help of Table 7, or an analogous table valid for the chosen initial chemical composition.

Let us consider now the accuracy of the age determination in the latter case. Assuming the probable error (p.e.) of (U - B)₀ to be ± 0.01 , we find for B2 - B8 stars, an average p.e. of the age equal to 4-percent. If for the stars in question the r.m.s. deviation of X from an average value is 0.05, the corresponding uncertainty of the age according to Table 6 gives a p.e. contribution of about 2-percent of the age. Similarly, if the r.m.s. deviation of Z from an average value is less than or equal to 0.01 (Reference 25), then the corresponding probable-error contribution is ≤ 7 -percent.

CONCLUSION

While this discussion suggests that ages of very satisfactory accuracy can be obtained for stars in the favorable region of the Hertzsprung-Russell diagram just considered, it should be

emphasized that our age calibration has been derived on the assumption that the stars are non-rotating and that the structure is not influenced by magnetic fields. Therefore, the actual uncertainty may be considerably greater than the uncertainties corresponding to the sources of error just discussed. Investigations based on precision photometry for stars in clusters and associations of the r.m.s. scatter of $(U - B)_0$ in the upper 40-percent part of the main-sequence band should contribute to the clarification of this question.

For A stars later than A2, age determination for field stars can be carried out in an analogous way on the basis of photoelectric uvby and $H\beta$ photometry use being made of a $c_1 - \beta$ diagram (References 21 and 28). For unreddened stars a $c_1 - (b - y)$ diagram serves the same purpose (Reference 25). For stars around A0 the problem is more difficult, but it is solved when the location of the star in a $(B - V)_0 - \beta$ diagram can be determined (Reference 21).

Applications of the procedures for age determination of main-sequence B and A stars described in this paper are discussed in a separate investigation.

ACKNOWLEDGMENTS

The authors are very grateful to Dr. A. Cox for putting the Los Alamos IBM 7090 code for computing continuous absorption opacities at their disposal, to Dr. A. Arking and J. Herring for making available their tables of corrections to opacities due to line absorption in advance of publication, and to Dr. H. Reeves for a preprint of his discussion of the problems of stellar energy generation. The bulk of the computer calculations were made at the Goddard Space Flight Center, Greenbelt, Md. However, the calculations of continuous-absorption opacities and part of the stellar-model calculations were made at the Institute for Space Studies in New York. We wish to thank Dr. A. Arking and Mr. J. DeVries for their help with these calculations, and Dr. R. Jastrow for the opportunity to use the facilities of the Institute for Space Studies in New York and for his interest in this investigation.

This work was supported in part by a grant to B. Strömgren from the National Science Foundation and in part by the U. S. Office of Naval Research (Contract Nonr 1858 (33)).

(Manuscript received February 26, 1965)

REFERENCES

1. Tayler, R. J., "Evolution of Massive Stars," *The Astrophysical Journal*, Vol. 120, no. 2, pp 332-341, Chicago: The University of Chicago Press, September 1954.
2. Kushwaha, R. S., "The Evolution of Early Main-Sequence Stars," *The Astrophysical Journal*, Vol. 125, no. 1, pp 242-259, Chicago: The University of Chicago Press, September 1957.
3. Blackler, J. M., "Models for Main-Sequence Stars," *Monthly Notices of the Royal Astronomical Society*, Vol. 118, no. 1, pp 37-44, London: Royal Astronomical Society, 1958.

4. Henyey, L. G., LeLevier, R., and Levee, R. D., "Evolution of Main-Sequence Stars," *The Astrophysical Journal*, Vol. 129, no. 1, pp 2-19, Chicago: The University of Chicago Press, January 1959.
5. Haselgrove, C. B., and Hoyle, F., "Main-Sequence Stars," *Monthly Notices of the Royal Astronomical Society*, Vol. 119, no. 2, pp 112-123, London: Royal Astronomical Society, 1959.
6. Hoyle, F., "On the Main-Sequence Band and the Hertzsprung Gap," *Monthly Notices of the Royal Astronomical Society*, Vol. 120, no. 1 pp 22-32, London: Royal Astronomical Society, 1960.
7. Caughlan, G. R., and Fowler, W. A., "The Mean Lifetime of Carbon, Nitrogen, and Oxygen Nuclei in the CNO Bi-Cycle," *The Astrophysical Journal*, Vol. 136, no. 2, pp 453-464, Chicago: The University of Chicago Press, September 1962.
8. Härm, R., and Schwarzschild, M., "Inhomogeneous Stellar Models. IV. Models with Continuously Varying Chemical Composition," *The Astrophysical Journal*, Vol. 121, no. 2, pp 445-453, Chicago: The University of Chicago Press, March 1955.
9. Aller, L. H., *The Abundance of the Elements*, New York: Interscience Publishers, 1961.
10. Morton, D. C., "An Observational Test of the Carbon-Cycle Rate," *The Astrophysical Journal*, Vol. 129, no. 1, pp 20-25, Chicago: The University of Chicago Press, January 1959.
11. Iben, I., Jr., and Ehrman, J. R., "The Internal Structure of Middle Main-Sequence Stars," *The Astrophysical Journal*, Vol. 135, no. 3, pp 770-778, Chicago: The University of Chicago Press, May 1962.
12. Eggen, O. J., "The Empirical Mass-Luminosity Relation," *The Astrophysical Journal Supplement*, Vol. 8, no. 76, pp 125-175, Chicago: The University of Chicago Press, July 1963.
13. Iben, I., Jr., "A Comparison Between Homogeneous Stellar Models and the Observations," *The Astrophysical Journal*, Vol. 138, no. 2, pp 452-470, Chicago: The University of Chicago Press, August 1963.
14. Osterbrock, D. E., and Rogerson, J. B., "The Helium and Heavy-Element Content of Gaseous Nebulae and the Sun," *Publications of the Astronomical Society of the Pacific*, Vol. 73, no. 431, pp 129-134, San Francisco: Astronomical Society of the Pacific, April 1961.
15. Gaustad, J. E., "The Solar Helium Abundance," *The Astrophysical Journal*, Vol. 139, no. 1, pp 406-408, Chicago: The University of Chicago Press, January 1964.
16. Biswas, S., Fichtel, C. E., Guss, D. E., and Waddington, C. J., "Hydrogen, Helium, and Heavy Nuclei from the Solar Event on November 15, 1960," *Journal of Geophysical Research*, Vol. 68, no. 10, pp 3109-3122, Richmond: American Geophysical Union, May 15, 1963.
17. Sears, R. L., "Helium Content and Neutrino Fluxes in Solar Models," *The Astrophysical Journal*, Vol. 140, no. 2, pp 477-484, Chicago: The University of Chicago Press, August 15, 1964.

18. Demarque, P. R., and Percy, J. R., "A Series of Solar Models," *The Astrophysical Journal*, Vol. 140, no. 2, pp 541-543, Chicago: The University of Chicago Press, August 15, 1964.
19. Parker, R., Greenstein, J. L., Helfer, H. L., and Wallerstein, G., "Abundances in G Dwarf Stars. IV. A Redetermination of the Abundances in G Dwarfs in the Hyades," *The Astrophysical Journal*, Vol. 133, no. 1, pp 101-106, Chicago: The University of Chicago Press, January 1961.
20. Wallerstein, G., "Abundances in G Dwarfs. VI. A Survey of Field Stars," *The Astrophysical Journal Supplement*, Vol. 6, no. 61, pp 407-444, Chicago: The University of Chicago Press, February 1962.
21. Strömberg, B., "Quantitative Classification Methods," in: *Basic Astronomical Data, Stars and Stellar Systems*, Vol. 3, ed. by K. A. Strand, Chicago: The University of Chicago Press, 1963, pp 123-191.
22. Polak, E. J., "The Transition from Hydrogen-Burning to Helium-Burning in a Star of Five Solar Masses," *The Astrophysical Journal*, Vol. 136, no. 2, pp 465-475, Chicago: The University of Chicago Press, September 1962.
23. Hayashi, C., Nishida, M., and Sugimoto, D., "Evolution of a Star with Intermediate Mass after Hydrogen Burning. I," *Progress of Theoretical Physics*, Vol. 27, no. 6, pp 1233-1252, Kyoto, Japan: Research Institute for Fundamental Physics, June 1962.
24. Harris, D. L., III, Strand, K. A., and Worley, C. E., "Empirical Data on Stellar Masses, Luminosities, and Radii," in: *Basic Astronomical Data, Stars and Stellar Systems*, Vol. 3, ed. by K. A. Strand, Chicago: The University of Chicago Press, 1963, pp. 273-292.
25. Strömberg, B., "Problems of Internal Constitution and Kinematics of Main-Sequence Stars," *The Quarterly Journal of the Royal Astronomical Society*, Vol. 4, no. 1, pp 8-36, London: Royal Astronomical Society, March 1963.
26. Strömberg, B., "Comparison of Observed and Theoretically Calculated Intensities in the Continuous Spectra of Main-Sequence B Stars," *Reviews of Modern Physics*, Vol. 36, no. 2, pp 532-545, New York: American Institute of Physics, April 1964.
27. Crawford, D. L., "Two Dimensional Spectral Classification by Narrow-Band Photometry for B Stars in Clusters and Associations," *The Astrophysical Journal*, Vol. 128, no. 2, pp 185-206, Chicago: The University of Chicago Press, September 1958.
28. Strömberg, B., "Spectrophotometric Classification of the Population Groups," in: *Stellar Populations*, ed. by D. J. K. O'Connell, S. J., Amsterdam: North-Holland Publishing Co., 1958, pp 385-412.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546